

Gravitational Searches for Lorentz Violation with Matter and Astrophysics

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This contribution to the CPT'16 proceedings summarizes recent tests of Lorentz violation in the pure-gravity sector with cosmic rays and reviews recent progress in matter-gravity couplings.

1. Introduction

Lorentz violation¹ as a signal of new physics at the Planck scale² is actively sought in a wide variety of tests³ within the general test framework of the gravitational Standard-Model Extension (SME).⁴ A subset of these tests involve gravitational physics, which can probe Lorentz violation in the pure-gravity sector associated with both minimal⁵ and nonminimal^{6–8} operators, as well as Lorentz violation in matter-gravity couplings.^{9,10} While Lorentz violation in gravity has been sought in a number of systems,³ we focus here on recent tests exploring gravitational Čerenkov radiation in Sec. 2, and review the status of searches for the $\alpha(\bar{a}_{\text{eff}})_\mu$ coefficient in the matter sector in Sec. 3, including work with superconducting gravimeters.¹¹

2. Gravitational Čerenkov radiation

The Čerenkov radiation of photons by charged particles moving faster than the phase speed of light in ponderable media is a well-known phenomenon in Nature. If the analogous situation of particles exceeding the phase speed of gravity were to occur, as might be the case in General Relativity (GR) in the presence of certain media,¹² the gravitational Čerenkov radiation of gravitons would be expected.¹³ In the presence of suitable coefficients for Lorentz violation in the SME, both electrodynamic¹⁴ and gravitational⁶ Čerenkov radiation become possible in vacuum. In this section, we review the tight constraints that have been achieved by considering cosmic rays and mention other possible implications of vacuum gravitational Čerenkov radiation.⁶

As with all SME searches for Lorentz violation, our analysis begins with the expansion about GR and the Standard Model provided by the SME action. Here we consider the linearized pure-gravity sector, which has now been written explicitly for operators of arbitrary mass dimension d that preserve the usual gauge invariance of GR.⁸ Except where noted, we assume that the other sectors of the theory are conventional. Exploration of the dispersion relation generated by this action reveals that a class of coefficients for Lorentz violation manifest as a momentum-dependent metric perturbation that generates a momentum-dependent effective index of refraction for gravity. With an appropriate sign for the coefficients for Lorentz violation, this index is greater than 1 and particles may exceed the speed of gravity and radiate gravitons. Hence each observation of a high-energy particle can place a one-sided constraint on a combination of these coefficients.

To obtain constraints, we perform a calculation of the rate of graviton emission that parallels standard methods assuming for simplicity and definiteness that only coefficients at one arbitrary dimension d are nonzero. The calculation is provided for photons, massive scalars, and fermions, the only differences in the three cases being the details of the matrix element for the decay and the form of a dimensionless function of d in the results. The rate of power loss can then be integrated to generate a relation between the time of flight t for a candidate graviton-radiating particle, the energy of the particle at the beginning of its trip E_i , and the observed energy at the end of its trip E_f . This relation takes the form

$$t = \frac{\mathcal{F}^w(d)}{G_N(s^{(d)})^2} \left(\frac{1}{E_f^{2d-5}} - \frac{1}{E_i^{2d-5}} \right), \quad (1)$$

where G_N is Newton's constant, $\mathcal{F}^w(d)$ is a species w dependent function of d , and $s^{(d)}$ is a combination of coefficients for Lorentz violation at dimension d that depends in general on the direction of travel for the particle. This result is distinguished from earlier work on the subject of gravitational Čerenkov radiation¹⁵ by the connection to the field-theoretic framework of the SME, the consideration of anisotropic effects, the exploration of arbitrary dimension d , and the treatment of photons and fermions.

Conservative constraints can be placed using Eq. (1) by setting $1/E_i^{2d-5} = 0$, solving for $s^{(d)}$,

$$s^{(d)}(\hat{p}) \equiv (\bar{s}^{(d)})^{\mu\nu\alpha_1\ldots\alpha_{d-4}} \hat{p}_\mu \hat{p}_\nu \hat{p}_{\alpha_1} \ldots \hat{p}_{\alpha_{d-4}} < \sqrt{\frac{\mathcal{F}^w(d)}{G_N E_f^{2d-5} L}}, \quad (2)$$

and using suitable data on cosmic ray observations.¹⁶ Here L is the travel

distance. Given the dependence on E_f in Eq. (2), the highest energy events yield the tightest bounds. The highest energy cosmic rays are believed to be nuclei, and continuing toward conservative constraints, we assume that the gravitons are radiated by a partonic fermion in an iron nucleus carrying 10% of observed energy E_\oplus , which leads to $E_f = E_\oplus/560$. A consideration of the likely origin of these particles leads to a conservative estimate of $L = 10$ Mpc. We then use the available data on cosmic ray energies and direction of origin¹⁶ to place constraints on six models. Three of the models are constructed as the isotropic limit at $d = 4, 6, 8$ respectively. In each of these models we place a one-sided limit on the one isotropic coefficient involved at the level of 10^{-14} , 10^{-31} GeV⁻², and 10^{-48} GeV⁻⁴ respectively. The other three models involve two-sided constraints on the anisotropic coefficients at each d . At $d = 4$ we place eight constraints at the 10^{-13} level, while at $d = 6$ we constrain 24 coefficients at the level of 10^{-29} GeV⁻², and at $d = 8$ we constrain 48 coefficients at the 10^{-45} GeV⁻⁴ level.

The paper concludes by discussing some ways in which our work might be extended. Topics considered include the role of the matter sector, the impact of gravitational Čerenkov radiation by photons on cosmological models, and gravitons emitting electromagnetic Čerenkov radiation.

3. Matter-gravity couplings

In Ref. 9 the phenomenology of matter-gravity couplings was developed with a focus on spin-independent coefficients, particularly the counter-shaded¹⁰ $\alpha(\bar{a}_{\text{eff}})_\mu$ coefficients. As of the CPT'13 meeting,¹⁷ constraints on $\alpha(\bar{a}_{\text{eff}})_\mu$ had been placed using the following systems:^{3,17} precession of the perihelion of Mercury⁹ and Earth,⁹ torsion pendula,¹⁰ a torsion strip balance,¹⁸ atom interferometry,¹⁹ and co-magnetometry.²⁰ This work resulted in a number of measurements of the time component reaching the level of 10^{-11} GeV on both the neutron and the proton plus electron coefficients. For the spatial components, two combinations of the nine coefficients were constrained at the level of 10^{-6} GeV, and four combinations were weakly constrained at the 10^{-1} GeV level. Note that coverage is sufficient to span the space that is accessible without charged-matter experiments.

Since CPT'13, $\alpha(\bar{a}_{\text{eff}})_\mu$ (as well as $\bar{s}_{\mu\nu}$) has been considered in an analysis of planetary ephemerides.²¹ This work considerably extends the level of the independent constraints on $\alpha(\bar{a}_{\text{eff}})_J$ coefficients to 10^{-5} GeV to 10^{-3} GeV, and the analysis of gravimeter experiments extends the maximum reach for these coefficients even further.¹¹ The consideration of bound

kinetic energy in equivalence-principle tests²² has also been used to further separate the $\alpha(\bar{a}_{\text{eff}})_T$ coefficients and other matter-sector coefficients. Though the $\alpha(\bar{a}_{\text{eff}})_\mu$ coefficient space accessible with ordinary matter has now been covered more uniformly with initial constraints, opportunities for further improvements with currently available methods remain.^{9,23}

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